Event-Driven SmartSync System for Structural Health Monitoring of Tall Buildings

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ABSTRACT: This paper discusses a modular structural health monitoring framework interlinked by SmartSync technology that can be expanded and deployed with “plug-and-play” ease. SmartSync communications infrastructure is network-based, and it can adapt easily to the evolving needs of the user without hardware redesign and the need for lengthy cable runs, which would not only be costly but incredibly inefficient in tall buildings. This flexibility also allows SmartSync to seamlessly monitor both wind and seismic events to offer a truly multi-hazard platform for monitoring continuously or in an event-triggered framework. Furthermore, the software modules also addressed in this study deliver high quality monitoring with a range of data mining, dissemination & management, post-processing and system identification capabilities available through a combination of real-time and on-demand services. Proof-of-concept is achieved using the recent deployment in the world-tallest building, Burj Khalifa.

1 INTRODUCTION

The instrumentation of buildings and structures and real-time monitoring of their performance have been recently made realizable by major advances in instrumentation and computer technology. It is now possible to install instrumentation that continuously monitors the structural system and provides an ongoing feedback on its performance. The traditional structural health monitoring (SHM) system used for this task is a wired system, often termed "hub and spoke" due to the fact that the sensors are located throughout the structure and then wired to a central data acquisition device such as a datalogger. In the applications to tall buildings, where response at the highest floor is generally the sole observed quantity, the wired hub-and-spoke systems have proven to be exceptionally reliable, e.g., Chicago Full-Scale Monitoring Program (Kijewski-Correa et al. 2006). However, this type of system becomes increasingly less practical in full-scale when large numbers and types of sensors are distributed over the structure due to two significant issues associated with its cables: a) instrument cables are very costly and sometimes difficult to deploy in certain locations and maintain; b) lengthy cables essentially serve as antennas, allowing noise to infiltrate the system. In addition, authors have learned lessons from their ongoing experiences monitoring tall buildings in Chicago that underscores the daunting data management challenges associated with long-term projects and the need to streamline data acquisition and management functions, even when adopting event-driven monitoring.

To overcome some of these challenges, this study introduces a unique prototype SHM, SmartSync, which utilizes the building's existing Internet backbone as a system of "virtual" instrumentation cables and addresses data processing/mining for a flexible, long-term monitoring framework. A centralized server performs basic data acquisition, event triggering and database management, while also providing data visualization that can be securely accessed via a web browser. Additional on-demand modules using web-based on-line approach provide data analysis, database access for current/past data statistics, dissemination and system identification on demand in order to mitigate the need for human interventions. The SmartSync framework has been deployed in the world-tallest building, Burj Khalifa, which has confirmed its efficacy in practical application.

2 SMARTSYNC IN STRUCTURAL HEALTH MONITORING

2.1 *Hardware and SmartSync Architecture*

SmartSync communication is network-based, and it can adapt easily to the evolving needs of ownership without hardware redesign and the need for lengthy cable runs, which would not only be costly but incredibly inefficient in tall buildings. Given the reliability of modern networks, e.g., local area networks (LAN) and Internet, the issues of packet loss and synchronization encountered in wireless systems are nullified, without the need for lengthy instrumentation cables that increase cost and noise. Furthermore, since the system is modular and largely "plug-and-play", the units can be rapidly deployed at any location with access to power and an Internet connection. Within this framework, data streams from distributed sensors are pushed through network interfaces in real-time and seamlessly synchronized and aggregated by a centralized server, which performs basic data acquisition, event triggering and database management, while also providing a powerful interface for data visualization that can be securely accessed even by mobile devices, as shown in Figure 1. Additional off-line services provide intelligent data evaluation/processing and system identification on demand. The system enables a completely modular and scalable approach to structural health monitoring, which can readily interface a wide variety of sensors and data formats (analog and digital) and can even accommodate variable sampling rates. Furthermore, hardware costs are reduced since all acquisition functions are centralized at the server and only basic network interfacing (limited number of channels) are required at the location of each sensor. The flexibility of this modular system and its software-enabled features uniquely allow the system to be tailored for multi-hazard monitoring (concurrently for wind or seismic events), with dual triggering mechanisms designed to activate the sensor arrays in case of either hazard.

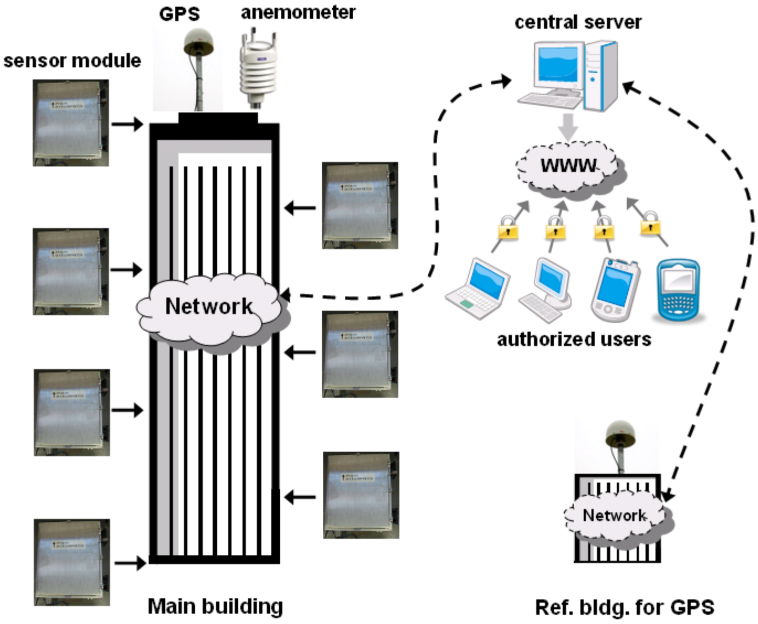

Figure 1. Conceptual diagram of SmartSync hardware configuration.

In SmartSync, sensor options are presented in a modular format that permits the customization of the SmartSync package uniquely suited for buildings. Each sensor module is housed in a ventilated, NEMA certified enclosure, which can be wall mounted at any location with access to building power and Internet. Within each enclosure, each sensor has various supporting electronics, including remote power regulators to provide remote control of power and reboot functions in event of a system failure to mitigate the need for on-site interventions following installation. This modular enclosure can support any number of sensors used in monitoring for tall buildings, e.g., accelerometers, global positioning systems (GPS) and meteorological stations.

2.2 *Software-Enabled Data Transfer and Management in SmartSync*

The software prototype for the SmartSync system has been designed to be multifunctional and consists of: a) event-based structural health monitoring in terms of triggering scheme; b) centralized data acquisition system for variable sensor types with different sampling rates; c) a real-time graphical interface system to observe the building's performance on-the-fly; d) a convenient data management system to efficiently store and retrieve the large volumes of data anticipated over the life of the deployment; and e) an web-based automated data processing framework to dramatically reduce need for human intervention on demand (Kijewski et al. 2003; Kwon et al. 2008).

All data acquisition operations, including synchronization, in SmartSync are programmed in LabVIEW (National Instruments) at the central server. To insure reliability of the system, TCP/IP (Transmission Control Protocol/Internet Protocol) is invoked as a stable stream delivery service that guarantees transmission of data sent from one host to another without duplication or loss, ideally suited for data from variable sensors coordinated over the LAN/Internet. As the data are received from each module, at variable sampling rates, buffers accumulate the data over predefined intervals (10 minutes), for real-time dissemination to authorized users, and statistics from all sensing modules are stored in terms of a database management system (DBMS), e.g., MySQL. Even though data storage is relatively inexpensive in the current market, for long-term monitoring programs such archiving of statistics proves to be far more efficient than continuously storing time histories that often are nothing more than low-level ambient vibration and then having the burden of mining those massive stores of data later.

The central server orchestrates event triggering, based on the responses of a master acceleration module. For wind monitoring applications, this would generally be the accelerometer at the uppermost floor, while in the seismic application, the accelerometers at the ground level would be queried. When responses of the master acceleration module surpass a given threshold, continuous time histories are archived synchronously for all the sensing modules and saved for subsequent detailed analysis on demand. The time histories collected by the central server within the monitored building are backed-up daily on the off-site server via FTP (File Transfer Protocol). Again, it should be emphasized that since triggering is handled by the server, which is based only on the response of a particular master accelerometer module and not designed a priori into the hardware, the system can be easily expanded and readily synchronized for either wind or seismic events. This flexibility allows for such dual hazard monitoring, as the trigger level and even data stream used as the master feed for triggering can be regulated with ease.

In addition to data acquisition and triggering, SmartSync also supports various data processing and rendering features through a secure web portal: real-time modules such as data visualization and the latest ten minute statistical display, and on-demand modules such as triggered data archive, daily statistical archive query and spectral analysis (Figure 2). To maximize user accessibility, all modules are designed to be web-based on-line/on-demand. In this manner, the geographically dispersed project team can easily access the data collected in this full-scale program from any location worldwide. The extent to which these processes, as well as basic data acquisition and analyses, can be automated to minimize human interventions was an equally important design consideration for this long-term SHM program.

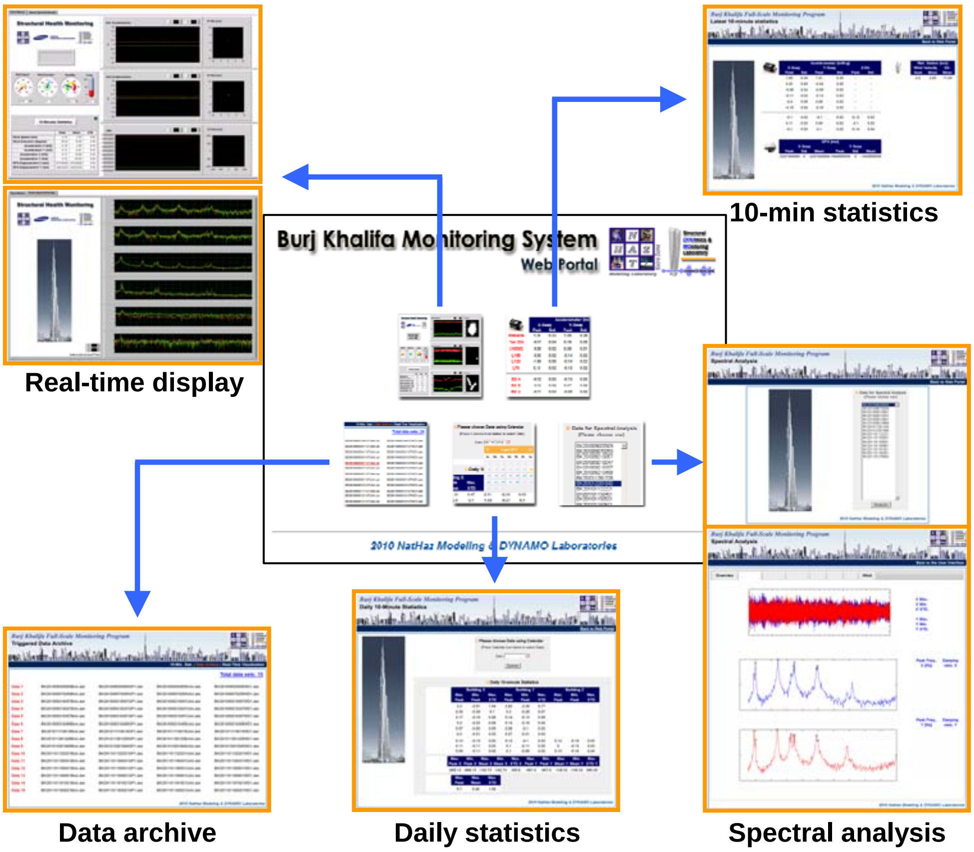

Figure 2. Web-based on-line modules in SmartSync framework

3 DEPLOYMENTS

3.1 *Prototype Deployment*

The first SmartSync prototype was deployed in Burj Dubai (Burj Khalifa) during the final stages of its construction in July 2008. This system included biaxial analog accelerometers, biaxial digital accelerometers, a GPS pair and a meteorological station to monitor wind-induced responses streaming in real-time via LAN/Internet. The digital accelerometers were included in this initial program simply for the purposes of validating the stability and sensitivity of a new all-digital device, while the analog accelerometers were used as the primary sensor for triggering the system. Figure 3 shows the externally installed GPS antenna and meteorological station, located on the balcony, as well as the internally installed enclosures anchored to the core wall. Differential GPS positions were determined by processing the motions of the tower against a reference GPS whose antenna was installed on the roof of the adjacent Office Annex.

3.2 *Permanent Deployment*

This system was later expanded in the Summer of 2010, relocating these units (with the exception of the prototype digital accelerometer) and adding additional hardware, as part of the permanent Building Movement Monitoring System (BMMS) (Abdelrazaq 2010). This expansion was executed in partnership with CPP, Inc. and included acceleration monitoring at six points along the height of the tower - all focused near the building centerline to capture only lateral responses in the primary axes of the structure, and including displacement and meteorological monitoring on the balcony of one of the uppermost floors. These locations represent readily accessible levels that still had significance for the dynamics of the structure or mark transition points between various aspects of the lateral system. In addition, tri-axial accelerations are monitoring each of the wings at the base of the structure. The GPS reference station was also relocated to the roof of the Office Annex as part of this final phase of deployment.

Figure 3. Schematic of SmartSync installation during construction of Burj Dubai (Khalifa), with inset photos of units as installed.

3.3 *Proof of Concept*

SmartSync has been deployed on Burj Khalifa since late 2008. Given its unique dual hazard software-enabled triggering functions, a verification of the system's ability to effectively trigger under either hazard is now presented as proof-of-concept. Since 2008, a number of earthquakes have originated from Southern Iran and sufficiently excited the building to trigger the system, one of those being the September 10, 2008 magnitude 6.1 quake that struck the region of Bandar Abbas, approximately 850 miles south of Tehran. Figure 4a displays the acceleration responses along the two primary axes of the structure as measured by the construction stage accelerometer module. The variations of the modal participation with time are explored using the wavelet analysis framework discussed in (Kijewski and Kareem 2003), whose resulting scalograms are also shown in Figure 4a and confirm the participation of approximately five modes in each of the response axes. The results affirm the dominance and persistence of the fundamental mode in the x-axis responses, with intermittent content at higher frequencies during the strongest shaking. Two of these contributions correspond to the predicted third and fifth sway modes in that direction. The y-direction response does not show the same dominance of the fundamental mode, with the most significant energy again being associated with higher frequency component, though for only short period. Two of the higher modes participating correspond to the predicted second and fourth sway modes in that direction. Figure 4b shows the resonant component of the GPS displacements during this event, dominated by the fundamental modes in the x and y-axes, reasonably agreeing with the wavelet analyses of the accelerations during this event.

The first substantial triggers of the system under wind occurred in March 2009; a sequence of triggered records from March 30, 2009 is provided in Figure 5. During the time of the most sustained response, the wind speed intensifies to a mean value of 37 km/h (23 mph), primarily from the east-southeast. Airport records indicate that thunderstorms were in the area at this time, which have been shown in other studies to produce noteworthy responses in similar structural systems (Bentz and Kijewski-Correa 2009), particularly since this wind direction is known to be one of the higher-impact angles from wind tunnel testing of Burj Khalifa (Baker et al. 2007).

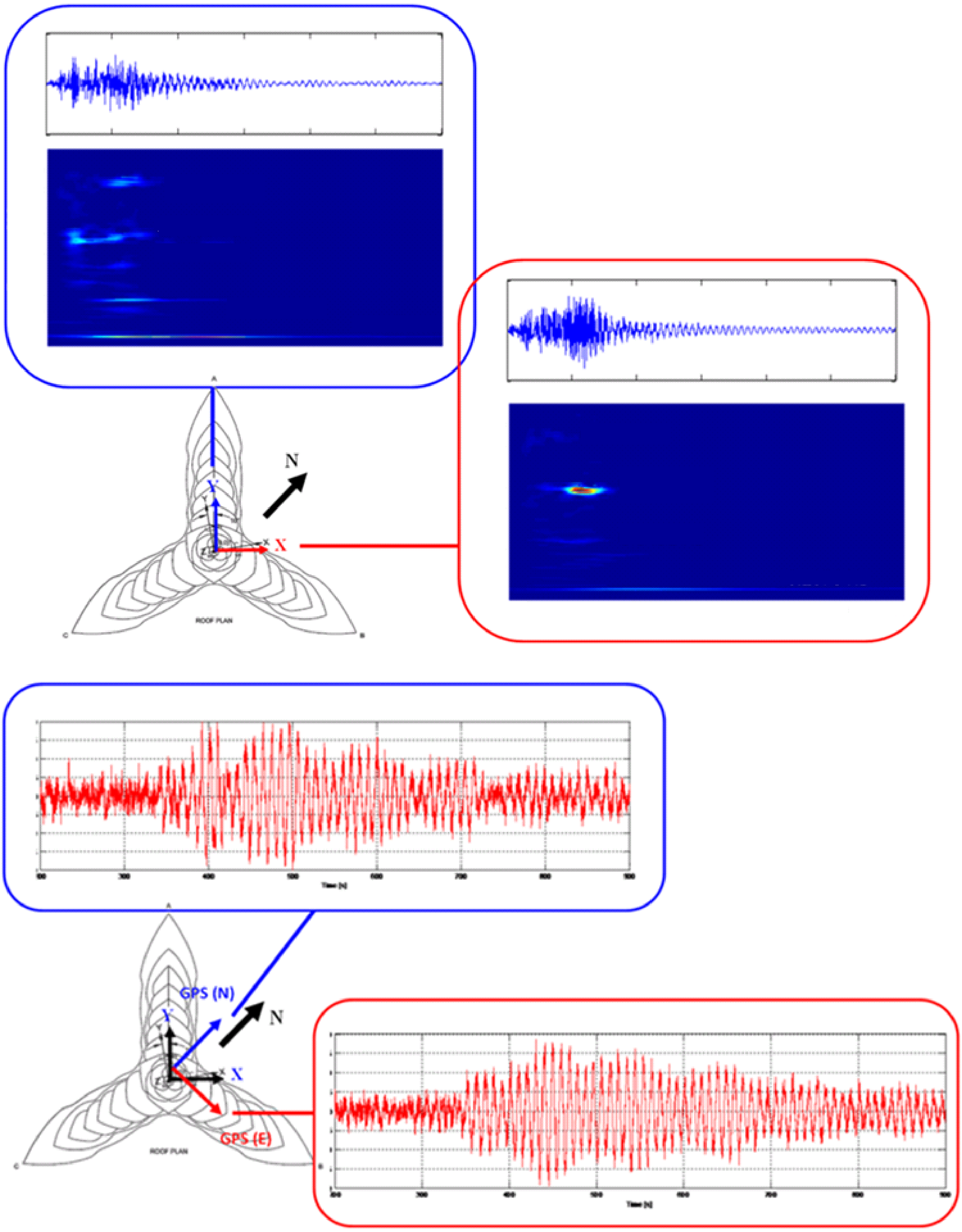

Figure 4. Measured responses in September 10, 2008 earthquake: a) acceleration time histories and wavelet scalograms on both axes; b) GPS displacements; inset depicts axis orientation for each sensor.

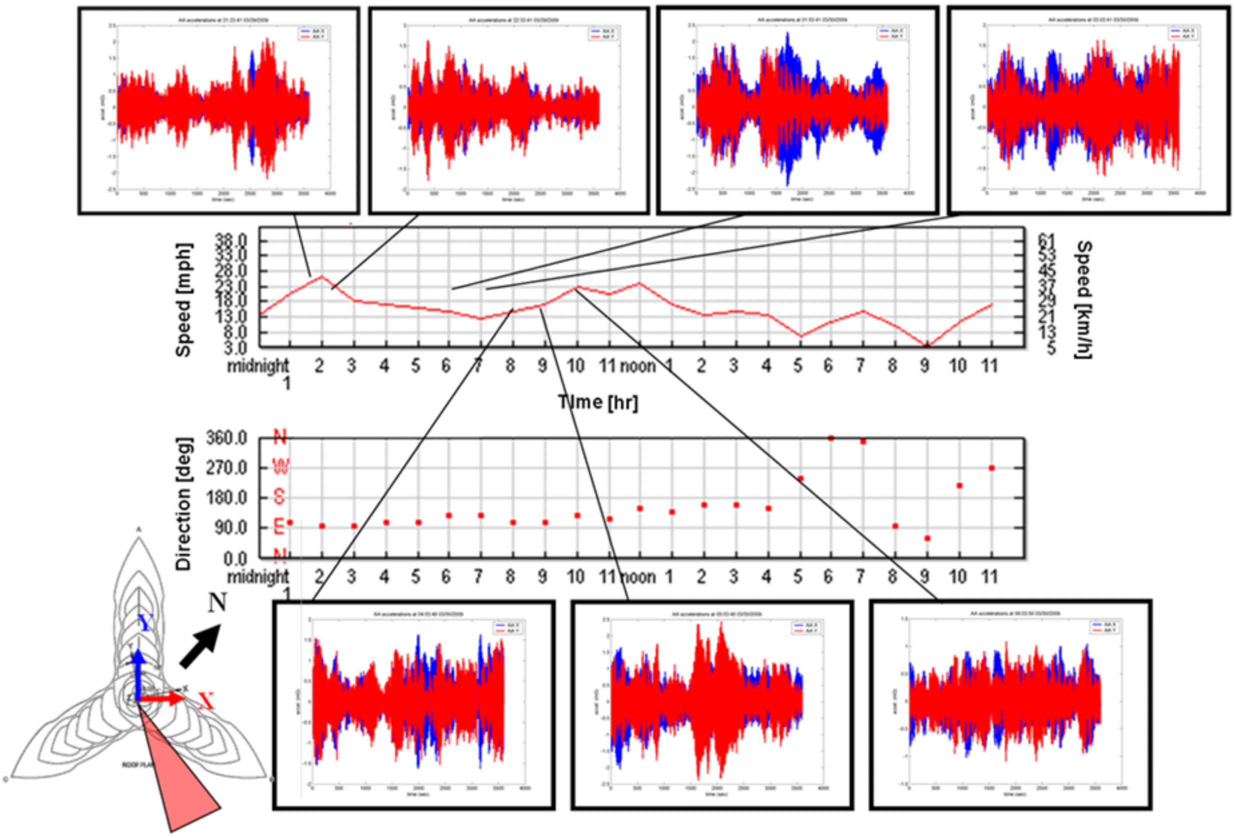

Figure 5. Measured wind-induced accelerations on March 30, 2009. Inset accelerations are shown indicating on the wind speed and direction plots the times at which they were triggered. Inset cross section of building indicates the angle of attack for the triggered wind events and the primary axes against which responses are measured.

4 CONCLUSION

This study introduces a unique prototype system for structural health monitoring, SmartSync, which utilizes the building's existing network backbone as a "virtual" cable network and addresses data processing/mining in a flexible and efficient manner to support long-term SHM. The system is primarily "plug-and-play", and thus the instrumentation system is rapidly deployable to any location with access to power and an Internet connection. Within this framework, data streaming from distributed sensors is pushed through network interfaces in real-time and is seamlessly synchronized and integrated by a centralized server, which performs the functions of basic data acquisition, event triggering and data management and processing, while at the same time providing a powerful interface for data visualization. The system enables a completely modular and scalable approach to structural health monitoring and can readily interface with a wide variety of sensor platforms, data formats (analog and digital), and even variable sampling rates. As its recent deployment during the construction stage and then permanent instrumentation of Burj Khalifa confirm, SmartSync provides it’s the flexibility and real-time data processing capabilities that allowed readily for its relocation, expansion and incorporation into an integrated permanent monitoring system to enable design validation and life-cycle decision-making truly worthy of the world's tallest building.

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